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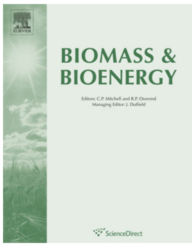

A GIS based assessment of bioenergy potential in England within existing energy systems

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ABSTRACT

This paper presents an analysis of the spatial supply and demand relationships for biomass energy potential for England, using Geographical Information System (GIS) mapping techniques. Due to energy use and cost of biomass feedstock transportation, the spatial relationship between potential supply and demand is crucial to efficient usage of this distributed feedstock. Previous studies have identified potential for biomass generation at individual sites, according to local factors dictating viable transport distances and costs. The research presented here necessarily takes a more generalised approach, to allow national scale assessment of capability to meet fixed location demands, and quantify theoretical potential generation under relevant scenarios. The approach is illustrated for England, although techniques are applicable elsewhere when suitable data are available.

Mapping for England indicates that of the 2,521,996 ha viable for cultivation of *Miscanthus*, 1,998,435 ha are within 25 km of the identified potential end uses of feedstock, and 2,409,541 ha are within 40 km. Potential generation exceeds the 2020 UK biomass generation target of 259 PJ, whichever radius is applied. However, predictions assume *Miscanthus* cultivation at all appropriate sites, and no policy interventions to limit transport distance.

Results from national scale analysis may be useful in informing government decisions, for example to identify impacts on total generation potential of incentives affecting decisions on allocation of overlap feedstock. Variation in GHG balance and environmental impacts between cultivation sites creates spatial variation in benefits of bioenergy, which should be taken into account in addition to the spatial relationship between supply and demand.

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1. Introduction

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) identifies significant climate change, linked to GHG emissions, primarily from fossil fuel usage, and suggests an increase in renewable, low carbon energy as a means of mitigation [1]. Renewable, low carbon sources of energy include wind, solar, hydropower, geothermal, wave and tidal, and biomass [2]. Of these, biomass is a significant non intermittent source [3]; the IPCC

Abbreviations: IPCC, Intergovernmental Panel on Climate Change; CHP, combined heat and power; GIS, Geographical Information System; DECC, Department of Energy and Climate Change; DH, district heating; ECS, Energy Crop Scheme; GHG, greenhouse gas; RHI, renewable heat incentive; LCA, lifecycle analysis; Defra, Department for Environment, Food and Rural Affairs; ROC, Renewable Obligation Certificate.

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suggested that bioenergy could be the greatest contributor to the renewable energy mix [4], with a potential of up to 1548 EJ a^{-1} by 2050 of which 96 EJ a^{-1} is from waste and residues. Such potential bioenergy would mean significant use of cultivated feedstock [5].

Energy crops can include annuals such as oil seed crops and sugarcane, or perennials with higher lignin content. Desired qualities include high yield, low input requirements and low levels of contaminants in the combusted feedstock [6]. Dedicated perennial crops tend to have lower input requirements compared to annuals; of these *Miscanthus giganteus* Keng, is a tall rhizotomous grass, which may be popular, since it achieves the highest potential energy ratio (calculated as energy generated divided by energy inputs) of 32:1 and has high rates of photosynthesis in a range of European and Asian climates, producing high yields [7]. *Miscanthus* also benefits from translocation of nutrients, reducing contaminants in the combusted feedstock, as well as providing nutrients for the next year's growth [8].

For a dedicated energy generation feedstock, with limited alternative market, farmers want security of demand before they will invest in cultivation and commit land [9]. Although the requirement for long-term feedstock supply to a plant should theoretically provide this demand security, operators may be unwilling to commit to a long-term supply contract. Whilst plant operators require guaranteed availability to construct a plant, they may prefer to maintain choice of suppliers in an uncertain market.

Biomass feedstock is a distributed resource with a low energy density, meaning that transport can make up a significant proportion of cost, as well as requiring fossil fuel use and associated emissions [10]. Therefore, transportation must be minimised, and a sourcing radius of 25 km has consequently been applied by several studies [11–13]. For England this was previously justified (e.g. Ref. [11]) by the stipulation from the Department for Environment, Food and Rural Affairs (Defra) that Energy Crop Scheme (ECS) funding was only available where an end use within 25 km could be demonstrated. Updated regulations [14] require end use to be within a "reasonable distance" meaning other economic factors will now dictate distance. Biomass can be processed to increase energy density and enable increased transport, and hence increased scale of generation. Integrated modelling of logistics and processing has been advocated [15] and will become more relevant if torrefaction moves past the demonstration stage [16].

Supply curves have been created for a range of crops (*Miscanthus* [17], corn stover and switchgrass [18]) based on cultivation and transport costs. Opportunity cost may also be relevant [18], hence it may be more appropriate to use market prices, since competition with other end uses can push up cost, e.g. animal bedding, and conversion to second generation biofuel. Supply curves can be used in conjunction with data on feedstock availability to establish total cost of meeting demand for an individual plant [17,18].

When allocating feedstock to an individual plant, it is therefore necessary to assess both supply and demand side economics, as well as spatial distribution of feedstock, to identify whether demand can be met at an acceptable cost. Supply costs will vary with road networks, cost of cultivation, local pattern of availability and availability of cheaper alternatives such as wastes or residues, as well as annual fluctuations in transport costs, feedstock costs and spatial patterns of yields [17,18]. Acceptable sourcing distance is plant specific, since generation efficiency and costs are affected by scale, and will also be sensitive to generation incentives such as the Renewable Obligation Certificate (ROC) [3]. As well as economics, environmental considerations should be applied to restrict transport distances, to ensure that GHG savings compared to fossil fuel generation are preserved. Although each individual plant will ultimately have a different transport radius, this level of assessment is not appropriate for national scale analysis.

Drax, the largest coal plant in England, currently sources from a supply radius of 96 km, but for smaller plants it should be possible to meet demand from a smaller radius [19]. Biomass demand for 10% co-firing at Drax is over double almost all other potential feedstock demands identified by this study. Anecdotally [20], a 40 km radius is applied as a limit in industry for smaller scale use of feedstock, and is supported in the literature [21]. A 40 km radius will therefore be implemented in this study, to make a general assessment of potential. Another radius might be more appropriate for assessment in another country, depending on local regulations, stipulations in incentives, or industry specifications. Based on market prices paid by Drax for 2012 (assuming an exchange rate of 1 GBP = 1.22 EUR based on 12 month average to 21/11/2012 [22]), of 77.30 € t^{-1} and road network tortuosity of 1.6 and transport costs of 2.79 € + 0.33 € km^{-1} [17] delivered feedstock from a 40 km radius would cost 101.84 € t^{-1}, and from 25 km would cost 94.48 € t^{-1}. However, these costs vary with fuel and market prices so may be different for subsequent years. It is interesting to compare potential generation applying a 40 km radius to the likely potential if a 25 km stipulation based on previous regulation is maintained.

The requirement to source feedstock locally reduces the potential scale of generation from biomass-only feedstock, which does not fit conveniently into conventional energy supply systems of efficient centralised generation at large scale [2]. This calls for an alternative approach to generation from biomass. Assessments of the future potential of bioenergy must take into account spatial factors for both supply and demand in order to minimise transport of feedstock whilst maximising efficiency of generation [11,22,24].

There are two main approaches through which penetration of generation from biomass may be increased in countries with developed energy systems. First, integrating with the existing large-scale centralised generation systems by co-firing with coal [e.g. Refs. [24,25]]; or second, through decentralised generation of combined heat and power (CHP) which can achieve higher efficiency at small scales by avoiding waste of generated heat [e.g. Refs. [23,26]]. For countries with less developed infrastructure, or significant off-grid rural areas, assessment based on supply and population density would be a more appropriate methodology [27].

1.1. *Co-firing*

In 2010, co-firing with coal was operational using a range of feedstocks at 228 plants worldwide [28]. By using feedstock in large plants, efficiency benefits of large scale generation are maintained [24,29]. Co-firing up to 10% requires little investment in plant conversion, and can be implemented more rapidly compared to the establishment of new biomass-only generating facilities [24,31]. Since the proportion of co-fired biomass can be varied, flexibility is maintained; the plant does not commit to a certain feedstock, which removes the uncertainty issue of feedstock availability for the plant operator, but not the issue of demand security for the farmer [24]. There is also the added certainty of using established technology [31]. If a shortfall in meeting required renewables targets is anticipated, the flexibility and speed with which the proportion of co-firing can be increased may enable the gap to be bridged at relatively short notice, if feedstock is available.

1.2. *CHP*

Since generation of electricity from biomass is a thermal process and a significant proportion of the energy stored in the biomass will be released as heat, using this otherwise wasted heat has the potential to increase the efficiency of energy production [10,32,33]. Improvements in efficiency and carbon savings through CHP generation, compared to separate generation of heat and electricity, are dependent upon the appropriate reference systems [34]. Since generation using biomass feedstock must be small scale to minimise transport, it is likely that generation of electricity alone would achieve low efficiency [2,10].

Transmission losses and costs of distribution infrastructure are significant; therefore, heat must be generated close to demand, meaning that distributed generation of heat is more efficient than centralised generation [34]. Since co-generation is more efficient at small scales, a distributed feedstock such as biomass can be efficiently used for this distributed approach to generation.

Total efficiency of CHP drops with electric power increase, so in order to maximise efficiency gains compared to electricity alone, heat generation should be maximised, but should not exceed heat demand [16,34]. Policy can also be a factor in the decision to shift generation towards heat or electricity, so it is important that financial incentives do not encourage less efficient use of plants.

CHP is most efficient where the heat off-taker has a large, consistent demand; industry tends to require higher temperatures than domestic users, with less seasonal variation, enabling more efficient supply [32]. However, a generation plant may produce heat energy at a range of temperatures. Hence, reducing the demand temperature increases the proportion of this heat that can be used and, therefore, may be a more efficient application [36]. Although existing domestic heat demand is significant in many countries, it is important to take into account that new housing will be built to higher thermal efficiency specifications, which can reduce peak heat demand by 50–90% [32,37]. Although this would reduce the generation displaced by DH, this may improve energy efficiency and economic benefits of CHP [36], since distribution losses are reduced for supply at low temperature, and the electricity proportion of generation can increase [34,38]. The infrastructure costs of DH installation may be prohibitive in many cases. However, payback periods can be as low as 4 years, compared to an average system lifetime of 25 years [39]. Since both DH and large demand applications of bioenergy CHP have the potential for improved efficiency and economics compared to separate heat and electricity generation, the potential for both should be assessed to some extent.

1.3. *Linking supply and demand*

Biomass supply and demand issues have been the subject of much research, for example by the Towards a Sustainable Energy Economy (TSEC) group [11,15,40,41]. The need to minimise transport reduces the potential scale of bioenergy generation, which complicates the fit with existing top-down energy systems. High biomass feedstock transport costs make the spatial relationship of supply and demand crucial to biomass generation efficiency, particularly for CHP, since heat must be generated close to demand [10,23].

The relationship between supply and DH demand has been assessed previously using modelling [23] and Geographical Information System (GIS) [42] analyses. For the UK, GIS has also been used with supply curves for co-firing at a single plant [17] and supply based analysis has been used to identify 40 km radius supply areas with most feedstock potential [11]. The study presented in this paper extends these ideas to use a GIS mapping approach at a national scale, to assess the relationship between the potential supply of local feedstock and the identified likely demand forms, and thus identify theoretical potential generation. The approach is illustrated for *Miscanthus* feedstock, and CHP and co-firing demands in England, using ArcMap GIS software [43].

2. Methodology

For convenience, the full GIS approach relating potential annual yield data spatially to identified potential end uses of the feedstock is outlined in Fig. 1.

In order to contextualise availability of feedstock, a hindcasting approach using the methodology given in Tables 1 and 2 is used to calculate the oven-dry Mt of *Miscanthus* required to meet the potential energy demand.

2.1. *Supply and demand*

It is convenient to choose a single feedstock type for the purposes of analysis, although the analysis can be repeated for other crops and feedstock sources such as wastes. *Miscanthus* was chosen for this analysis due to its favourable qualities in terms of yield and input requirements, and availability of data for England on land suitability for *Miscanthus* cultivation and predicted yield [44]. To identify areas for yield prediction, unsuitable land types were ruled out, including organic or artificial soil, natural habitats, forests, slopes over 15°, urban areas, lakes and rivers. A description of the methodology for yield prediction and constraints mapping as applied to England are detailed elsewhere [44,45]. Yield predictions are crucial, due to significant spatial variability, the threshold of economically viable annual yields, and the use of predicted yields in forecasting generation potential.

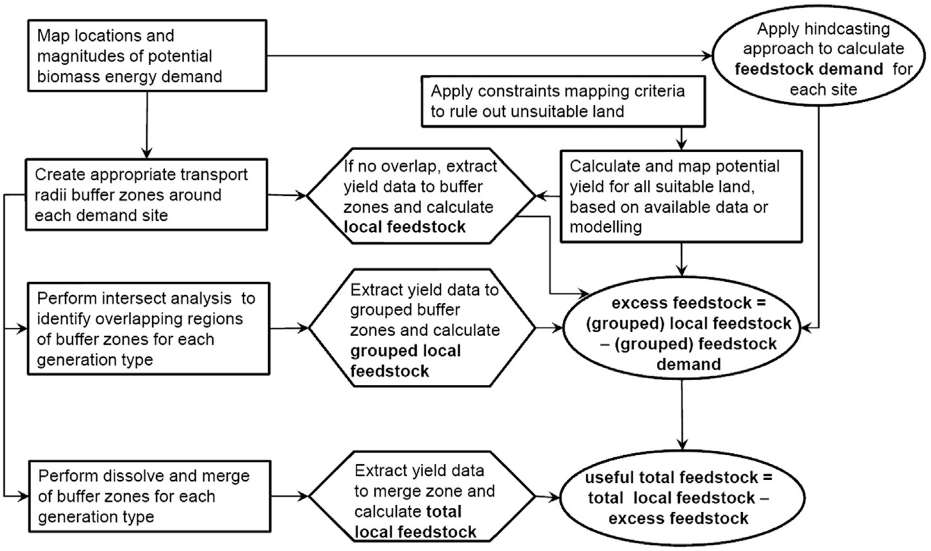
Map locations and magnitudes of potential biomass energy demand
Apply hindcasting approach to calculate **feedstock demand** for each site
Apply constraints mapping criteria to rule out unsuitable land
Create appropriate transport radii buffer zones around each demand site
If no overlap, extract yield data to buffer zones and calculate **local feedstock**
Calculate and map potential yield for all suitable land, based on available data or modelling
Perform intersect analysis to identify overlapping regions of buffer zones for each generation type
Extract yield data to grouped buffer zones and calculate **grouped local feedstock**
excess feedstock = (grouped) local feedstock – (grouped) feedstock demand
Perform dissolve and merge of buffer zones for each generation type
Extract yield data to merge zone and calculate **total local feedstock**
useful total feedstock = total local feedstock – excess feedstock

Fig. 1 – GIS based methodology to calculate potential generation from biomass, according to spatial patterns of supply and demand. Calculation of grouped local feedstock is only required where demand sites are clustered. To calculate national total potential, taking into account overlap between different demand types, feedstock allocated to priority demands should be calculated by performing an extract to the intersecting zone. The overlap feedstock must be subtracted from local feedstock prior to calculation of excess feedstock for an individual site (or group of sites), and also subtracted from the total merged local feedstock value, prior to final calculation.

Locations of potential end users of feedstock in the three categories below were identified, and calculations were performed to identify the potential demand for feedstock in oven-dry Mt of *Miscanthus*.

2.2. *Co-firing*

Location data for existing coal generation were used to map existing plants for England with data available from energy providers [30]. Potential demand for biomass feedstock for co-firing in existing coal powered stations is likely to be up to 10% of total fuel. A greater proportion, up to 20%, is feasible but would require willingness of owners to invest in modifications to deal with by-products and potential sources of corrosion [25]. The tonnage of feedstock required is calculated based on plant output, using a measure of efficiency to calculate the energy input required, and dividing by the energy density of *Miscanthus* to calculate the mass required. Currently, utilisation of coal plants in the UK is as low as 40%, but has been up to 65% in the last ten years [46]. Increased use of coal plants is anticipated under co-firing scenarios [47], and Defra suggest a factor of 60% [48]. Detailed steps calculating demand for co-firing up to 10% are outlined in Table 1.

2.3. *Industrial and other large demand CHP sites*

Potential locations for industrial scale CHP were established from the UK Government's Department for Energy and Climate Change (DECC) heat map [49] with data compiled for all large heat demands not already utilising CHP. These data may be more difficult to acquire at national scale for countries where heat demand maps are not available, although they may be relatively easily compiled at regional scale. The tonnage of feedstock required to supply a CHP plant meeting heat demand is calculated from the heat energy requirement, maximum thermal energy generation efficiency and energy density of *Miscanthus*, according to the steps outlined in Table 2. Calculations assume that generation would target meeting heat demand, although excess feedstock may be used to

Table 1 – Calculations used to establish tonnage of biomass required for 10% co-firing at a coal fired plant.

Power	Energy output = power × utilization factor × hours in a year, 1 kWh = 3.6 MJ	Energy input required; based on average efficiency [24]	Biomass energy assuming 10% co-firing	Oven-dry *Miscanthus* demand at 17 GJ t^{-1} [78]
kW	Capacity × 0.6 × 8760 × 3.6 MJ	Energy × (100/30)	Input × (10/100)	(Biomass energy)/17,000

Utilization factor is taken from the UK biomass strategy [48]. These calculations can be performed in reverse to calculate energy generation from figures for available feedstock.

Table 2 – Calculations used to establish tonnage of biomass required to provide industrial CHP.

Heat demand	Heat energy demand = power × utilization factor × hours in a year, 1 kWh = 3.6 MJ	Energy input required; based on maximum thermal efficiency [78]	Oven-dry *Miscanthus* demand at 17 GJ t^{-1} [78]
kW	Demand × 0.568 × 8760 × 3.6 MJ	Output × (100/70)	(Energy input)/1,700,000

Utilization factor is based on UK statistics [50]. These calculations can be performed in reverse to calculate energy generation from figures for available feedstock. Hindcasting calculations are based on meeting heat demand. Therefore, efficiency values for generation to maximise heat production are applied to calculate energy input; 70% efficiency of conversion to heat can be expected and 20% efficiency for conversion to electricity are applied when reversing calculations to calculate total energy generation [79].

increase the electricity component of generation. A utilisation factor must be applied to account for downtime of the heat demand; for example, existing CHP in the UK has 54% utilisation, although variation with end use is likely [50].

2.4. *Residential/district heating CHP sites*

Due to expected profit margins, DH is likely to be installed only in regions with heat demand densities over 180 MJ m^{-2} a^{-1} [51]. Areas of profitable demand were identified for England based on annual total gas consumption statistics, obtained from government databases. Data were provided per district (divided by district area to obtain demand density) assuming 98% of gas usage is for space and water heating [52] and an 80% efficiency for conversion to heat in domestic boilers [34].

Modelling approaches to identify optimum potential DH plant locations in terms of energy supply and demand are illustrated elsewhere [23] and ideally incorporate detailed information on individual buildings [42] and, hence, were not included in this study. As well as modelling, additional consideration of site factors may be required to identify feasible locations for generation to supply an individual district. Furthermore, distribution losses for potential DH are dependent on the system specification, lengths of pipes and distribution temperatures [51]. Therefore, to facilitate national scale analysis, calculations have been limited to approximations based on locations of end-user demand. Calculations are based on total gas usage, so it is not relevant to apply a utilisation factor to allow for downtime. However, seasonal variability in heat demand is likely to be significant.

2.5. *Potential yields*

Table 3 identifies total potential for *Miscanthus* cultivation in England (based on predicted potential yield data [44]) and compares this figure to demands from hindcasting calculations. Without taking into account spatial factors, there is sufficient potential supply for both 10% co-firing with coal, and for all industrial and large-scale heat demand to be supplied by biomass CHP. However, the preferred 40 km radius for biomass road transport-based supply chains means that spatial analysis is required to assess potential to meet demand locally.

2.6. *GIS mapping*

The GIS approach developed in this study is based on application of mapping and spatial analysis actions detailed in Fig. 1. The approach is designed to be applied at national scale to provide an initial forecast of biomass generation potential, to identify regions or plants with limitations, and to calculate potential land area taken out of food production. The underlying logic is similar to the WISDOM methodology [27]; data on supply and demand are integrated due to economic and emissions restrictions requiring minimised transport and a need to view biomass as a local feedstock. It differs in scale

Table 3 – Potential *Miscanthus* yield calculations for the whole of England, compared to demand of identified potential end uses of feedstock.

Predicted oven-dry yield range (t ha^{-1} a^{-1})	Available land (ha)	Oven-dry *Miscanthus* production (Mt)
9 or less	591,900	N/A
9–12	520,600	5.47
12–15	1,211,900	16.36
15 or more	789,500	11.84
Total		33.67
Potential usage		Required oven-dry feedstock (Mt)
Co-firing at 10% of capacity		8.6
Industrial CHP for identified heat demand		2.2
Total		10.8

Yield data are from a previous study [44] modelling potential yield of *Miscanthus* for sites identified as suitable for cultivation based on 11 constraints [44]. Since 9 oven-dry t ha^{-1} a^{-1} is the minimum economically viable yield, areas with lower yield are considered unattractive for cultivation and are not included in calculations [44,59]. Total yields for viable areas are calculated conservatively, as the average for each yield range, or as the minimum for the 15 or more range.

from research such as [11,18], and from other national scale assessments such as [27,41] in the incorporation of multiple fixed-site potential end uses and analysis of interaction of demand zones. Out of necessity, national scale analysis must be simplified, compared to assessment of individual plants, e.g. in Refs. [11,17], and subsequent, more detailed analysis is recommended to calculate economic merits and GHG savings of individual plants.

For both coal fired stations and potential large demand CHP sites, a transport radius buffer was produced using the ArcMap software, and spatial potential *Miscanthus* yield data were extracted for each feedstock catchment area to give potential local feedstock.

The hindcasting approach outlined in Tables 1 and 2 was then applied to calculate potential feedstock demands, with excess feedstock calculated as:

$$\text{Excess feedstock} = (\text{Local feedstock} - \text{Overlap feedstock}) - \text{Feedstock demand.}$$

Since co-firing is flexible, for coal-fired plants, the proportion of biomass fired was assumed to be variable up to the 10% or 20% demand figure (calculated as per Table 1). Therefore, the total feedstock available for co-firing was calculated, applying the specified radius, and subtracting excesses up to both 10% and 20% demand for individual English coal plants.

Although calculations have not been made for DH, a map has been produced (Fig. 2) to visualise the general potential of feedstock availability for this purpose, with potential yield extracted to a 40 km buffer of districts with potential for DH installation.

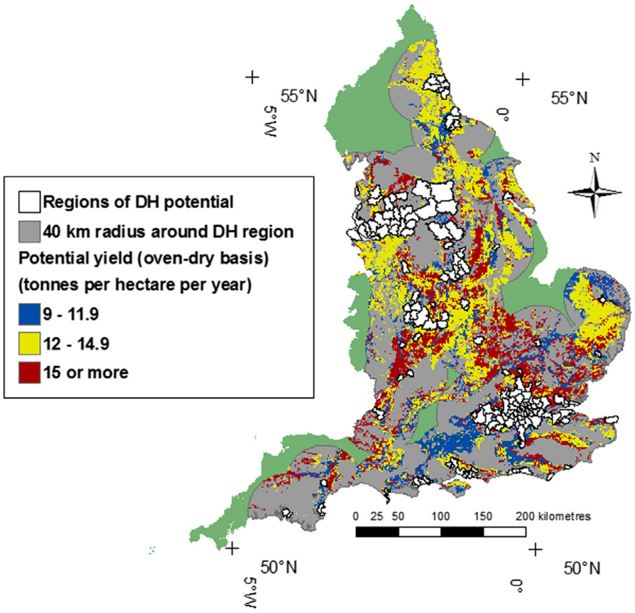
Regions of DH potential
40 km radius around DH region
Potential yield (oven-dry basis)
(tonnes per hectare per year)
9 - 11.9
12 - 14.9
15 or more
55°N
5°W
0°
55°N
N
0 25 50 100 150 200 kilometres
50°N
5°W
0°
50°N

Fig. 2 – Map to illustrate calculation of available feedstock for a group of individually viable demands. CHP sites are grouped for convenience of calculations, with groups selected to have intersections between all included buffers. Thick black lines indicate buffer zones for the group of CHP sites being assessed, and the predicted yield data extracted to this group is displayed.

For industrial and other large heat demands, feedstock requirement may be less flexible, and potential of sites individually is more important, although CHP may still be installed where the full heat demand cannot be met. The feedstock demand for each potential unit (calculated as per Table 2) was compared to potentially available feedstock within 40 km, to assess viability. Where there is excess feedstock available for CHP relative to heat demand, it is possible to increase the electricity component of generation to utilise this, although total efficiency may decrease as a result.

For both co-firing and CHP demands, there is clustering of sites, leading to overlapping buffer zones. To take into account proximity of other sites when calculating feedstock availability, it is convenient to perform calculations for adjacent sites as a group, by extracting feedstock to the combined area, as indicated in Fig. 3, and calculating excess feedstock where total demand of all relevant sites can be met. These calculations are only performed for sites with sufficient feedstock within the original designated transport radius.

Finally, total potential local feedstock was calculated in the GIS by performing a dissolve and merge on the original buffer zones, and again extracting potential yield data to this mask. The usable total feedstock for all England, for the identified demand type, can then be calculated according to:

$$\text{Useful total feedstock} = \text{Total local feedstock} - \text{Excess feedstock.}$$

There is likely to be overlap between, as well as within, demand types. An intersect analysis was performed in the GIS on the buffer zones to identify where feedstock catchment areas overlap, and predicted yield data were extracted for these zones to give overlap feedstock. When applying this method to predict maximum potential generation, overlap feedstock is included in calculations for the most efficient generation type to which it is applicable. Therefore, since large scale CHP has higher conversion efficiency than co-firing, feedstock which was also suitably located for CHP was subtracted from co-firing figures before calculation of excess.

3. Results

3.1. *Co-firing*

As shown in Fig. 4, the greatest coal-fired capacity and potential for local biomass cultivation is in the North East and centre of England, giving these locations the best potential for co-firing of locally-grown *Miscanthus*.

Table 4 shows that in England, 44 PJ could be generated from locally-sourced *Miscanthus* with co-firing at 10%, or 47 PJ at 20%. Of 13 oven-dry Mt, 11 are also suitably located for industrial CHP. If a 25 km transport restriction were imposed, 30.3 PJ could be generated with co-firing at 10%, or 32.3 PJ at 20%.

3.2. *CHP for district heating*

Fig. 2 shows that potential DH installations are distributed in clusters throughout England. The map shows significant

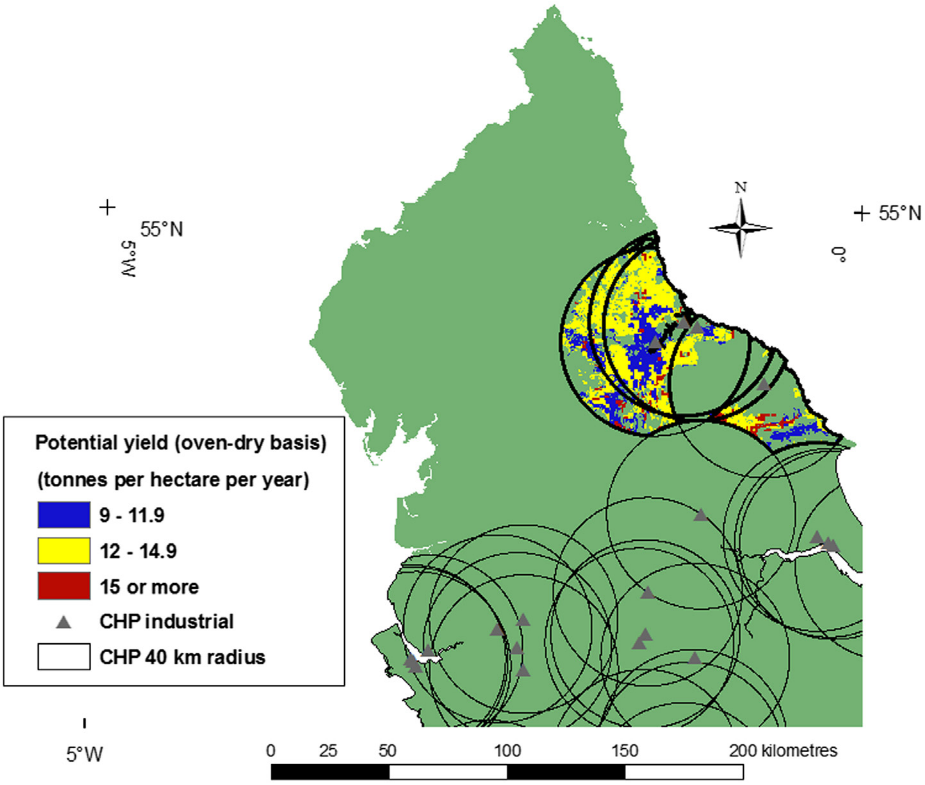

Fig. 3 – Map to show potential *Miscanthus* feedstock supply and demand for co-firing. Filled circles denote locations and magnitude of demand for 10% co-firing. Open circles indicate the 40 km radius around a demand site, coded for the proportion of total generation which could be supplied from local *Miscanthus* feedstock.

feedstock potentially available within 40 km of many of these sites. Calculations indicated that in England, 31 oven-dry Mt could be cultivated for this purpose, producing 366 PJ of DH (without taking into account transmission losses) as well as 104 PJ of electricity. These values do not exclude feedstock which is also suitably located for other end uses. Once these demands have been met, the total combined energy generation potential from DH is 307 PJ, although again, distribution losses will apply to the generated heat. In regions with potential for DH, there is a total end-user demand of 461 PJ of delivered heat, which would require 39 oven-dry Mt of biomass feedstock, before distribution losses have been taken into account. If a 25 km transport restriction were imposed, feedstock availability decreases to 24 oven-dry Mt, producing 288 PJ of heat and 82 PJ of electricity.

3.3. *CHP for industrial and large heat demand sites*

Fig. 5 shows that only one of the identified potential industrial CHP sites does not have sufficient potentially available *Miscanthus* feedstock within 40 km. Although this site has no competition for feedstock supply, a significant proportion of local land was ruled out at the constraints mapping stage. The majority of potential CHP sites identified have significant overlap of supply area. However, significant feedstock potential in these regions combined with mostly low demands mean CHP groups remain viable, and have excess feedstock when assessed as per Fig. 2. Total potential large demand CHP generation from local *Miscanthus* in England is 25 PJ of heat and 7 PJ of electricity. Calculated potential generation is not reduced by restricting feedstock transport to 25 km. However, since calculations are based on cultivation at 100% of suitable sites, such a restriction might still impact generation potential.

3.4. *Competition for feedstock*

Figs. 2–5 indicate that catchment zones of different potential end uses of biomass occupy similar areas. Overlap between feedstock catchment zones for different forms of demand can be significant, with calculations for England revealing that 11 oven-dry Mt of feedstock have potential end-use competition between co-firing and large scale CHP. Generalised catchment zones for regions of DH potential shown in Fig. 4 cover much of England, with 13 oven-dry Mt of *Miscanthus* covering areas coinciding with co-firing, and 21 oven-dry Mt coinciding with industrial CHP.

4. Discussion

4.1. *Co-firing*

Based on the results in Section 3.1, investing in plant adaptations for co-firing at greater than 10% capacity could significantly increase biomass generation if feedstock were sourced from up to 40 km, but would have less effect if the

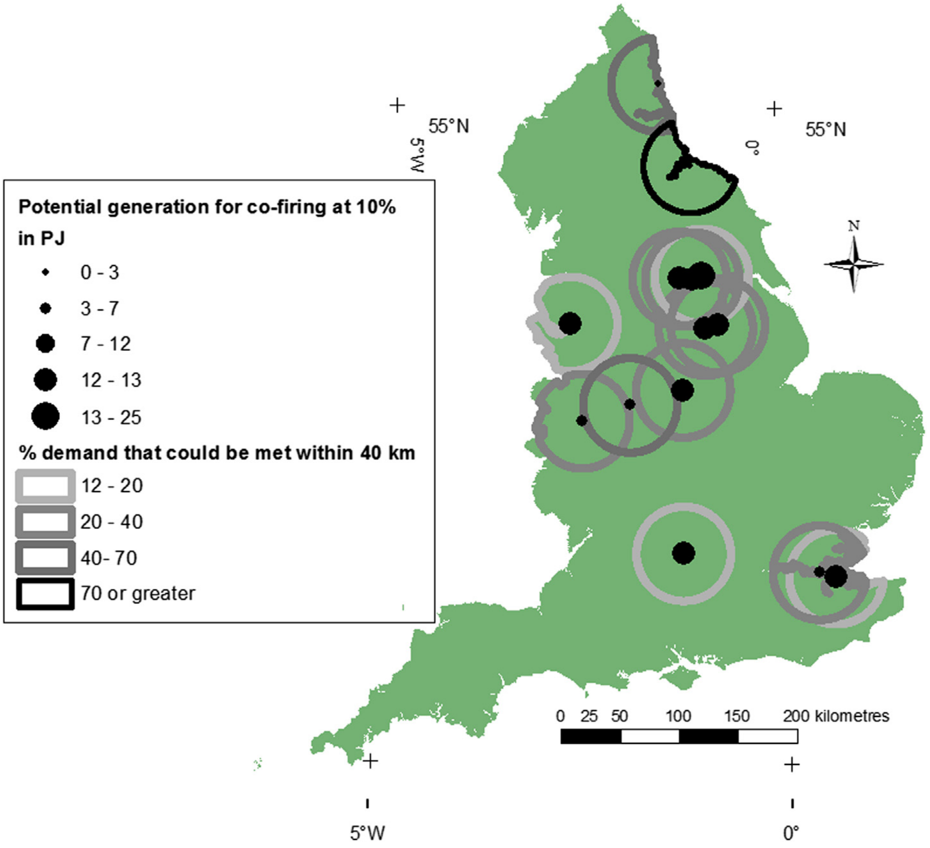
Potential generation for co-firing at 10% in PJ
0 - 3
3 - 7
7 - 12
12 - 13
13 - 25
% demand that could be met within 40 km
12 - 20
20 - 40
40- 70
70 or greater
55°N
55°N
5°W
0°
5°W
0°
N
0 25 50 100 150 200 kilometres

Fig. 4 – Map to show potential *Miscanthus* feedstock availability in relation to locations of potential district heating installations. White zones indicate regions with potential for profitable DH systems, and feedstock located within 40 km of these zones is displayed.

25 km transport limit were enforced. This demonstrates the utility of spatial analysis of feedstock availability in informing decisions about both plant adaptations and energy legislation. Flexibility in the proportion of generation from biomass, and of feedstock used, makes co-firing the most feasible area for expansion, although economic and policy factors remain a significant control on attainment of the theoretical potential identified above.

4.2. *District heating*

Not all of England's potential for DH can be realised through local *Miscanthus* feedstock. Feasibility of meeting this demand is dependent on heating requirements which vary with temperature, housing standards and population density, and the potential for cultivation close to higher population densities [23,42].

Previous work suggests that optimum locations for DH generation are at the edge of urban areas [23], with highest demand likely to coincide with urban centres such as capital cities. In England, London is entirely urbanised with no cultivation potential. However, data displayed in Fig. 3 indicate significant local feedstock potential to the north of the city.

In the UK in 2008, 58% of domestic energy consumption was for space heating and 24% for hot water [53] suggesting that biomass DH in England could significantly reduce carbon emissions. This potential is likely to be greater for cooler countries, and less for warmer countries.

Although some likely parameters for DH can be extrapolated from existing systems (for example, radius can be up to

Table 4 – Potential biomass availability for co-firing (assuming conservative potential cultivation within 25 km of all existing coal plants).

Percentage biomass to be co-fired	Total PJ that could be from biomass	Oven-dry *Miscanthus* demand (Mt)	Potentially available oven-dry *Miscanthus* (up to specified local demand) within 40 km supply radius (Mt)	Generation for potentially available *Miscanthus* (PJ)
10%	43	8.6	8	42
20%	86	17.2	9.2	47

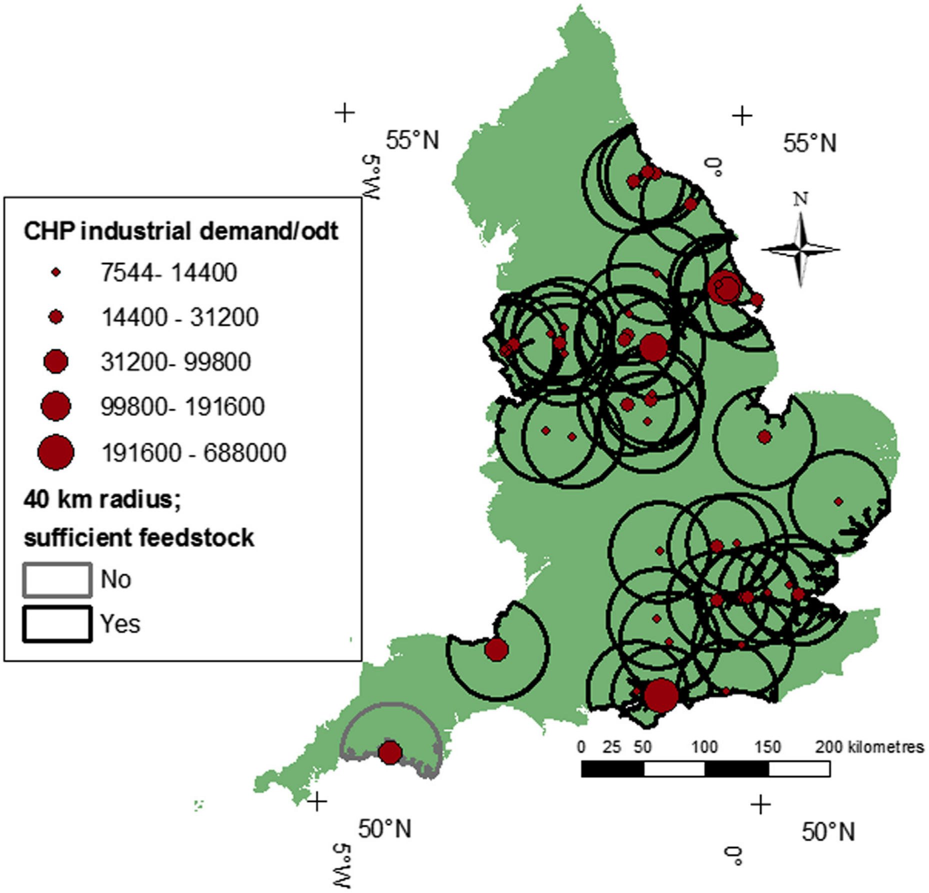

Fig. 5 – Map to show potential *Miscanthus* feedstock availability in relation to locations of potential demand for industrial and large scale combined heat and power. Filled circles denote locations and magnitude of potential industrial CHP demand. Open circles indicate the 40 km radius around a demand site, coded for plant viability.

30 km) many variables such as household level choice and local demand density variations must be taken into account [23,42]. Without known system specification, it is not possible to analyse this issue fully through this approach. The analysis presented here is best used for initial qualitative assessment of potential for DH, and for identifying competition with other potential feedstock end uses. Modelling approaches can be applied following on from this to identify optimum sites and capacity [23]. The socioeconomic barriers to uptake of DH significantly affect bioenergy potential; without DH, total potential generation for England drops to 76 PJ.

4.3. *Large scale CHP*

Whilst identified locations are indicative of heat demand, social and economic factors are critical to the potential for bioenergy CHP being used to meet this demand; non-renewable CHP, or generation of heat only, may be preferred. Proximity of sites with potential for industrial CHP means that there is significant overlap of catchment regions for adjacent sites, meaning that competition for feedstock must be considered as well as potential local yields. In the case of England, results in Section 3.3 indicate that appropriate allocation of this feedstock removes a limitation on plant viability. However, feedstock purchasing in a free market is likely to be based on proximity and not optimisation of national generation, and hence competition may have economic impacts. The issue of overlapping demand zones is likely to be common, since industry, and therefore industrial heat demand, is likely to be clustered in most countries, due to spatial patterns of transport links and raw material availability [54].

4.4. *Overlap*

Overlap of feedstock catchment zones for different forms of demand must also be taken into account since demand sites of each type tend to cluster in similar locations [54]. Feedstock from areas identified in England as within 40 km of both industrial CHP and coal plants has a generation value of 38 PJ of electricity and 134 PJ of heat as CHP, or 57 PJ of electricity from co-firing with coal.

Although in the scenario analysed here there is sufficient feedstock not to make allocation decisions between industrial CHP and co-firing, in theory this difference in efficiency indicates that CHP may be a better choice if the objective is to increase the proportion of generation from renewables. However, the associated CO_2 mitigation achieved through deployment of bioenergy generation is dependent on the reference system (i.e. the emissions from the generation replaced) as well as the lifecycle analysis (LCA) of the bioenergy process (including cultivation and transport of feedstock as well as the power generation step). Bioenergy LCA requires consistent, well defined, ideally inclusive system boundaries, as well as incorporation of site specific factors, particularly in terms of GHG balance of cultivation [55]. Therefore, if GHG emissions reduction is taken into account as a secondary aim, many other factors must be considered when comparing potential bioenergy generation. There is need for a system-specific LCA to gain a true picture of any benefits in terms of energy and GHG savings of CHP in practise [34].

Before transmission losses have been considered, DH efficiency is more than double co-firing efficiency, with potential generation from overlap feedstock of 193 PJ compared to 65 PJ. However, DH was prioritised last for overlap feedstock in the calculations presented here due to significant socioeconomic obstacles in England.

When comparing DH and industry as end users of CHP there are further variables affecting efficiency, and therefore generation proportion. The large, consistent demand of industrial-type users enables more efficient generation patterns [32]; however, the lower temperatures required by domestic end users enable a more efficient use of the full temperature spectrum of generated heat [34]. Therefore, combination of industry and DH may be the most efficient approach in terms of heat utilisation, although generation companies tend to prefer a single heat off-taker due to the complexity of contractual agreements [56]. Large demand sites such as hospitals, airports and public buildings may combine the benefits of lower domestic temperature requirements, with the large demand advantage of reduced infrastructure requirements, making an optimum location for CHP [57].

Policy, regulation, economics and local choices will affect the generation balance and capacity achieved. The end use may affect the carbon and energy savings, and policy reflecting this may encourage optimum utilisation of potentially available biomass feedstock.

4.5. *Indications in terms of targets*

DECC [3] anticipates that electricity and heat from biomass could produce up to 259 PJ or 30% of the UK renewables target. From the results presented in this study, assuming preference order for overlapping feedstock of large demand CHP, then co-firing, then DH (with excess local feedstock from other applications also used for DH), a total of 383 PJ of energy could be generated annually from local *Miscanthus*. This indicates that the DECC (2009) UK biomass generation target of 259 PJ has significant potential to be achieved using locally grown *Miscanthus*, for the generation end uses identified in England alone, depending on uptake by farmers and generators. The target could, in fact, theoretically be met taking feedstock only from within the 25 km radius originally stipulated. However, since *Miscanthus* is unlikely to be grown at all potential sites, increasing the allowable transport distance improves prospects for bioenergy.

The UK Biomass Strategy [48] aims for 350,000 ha of land to be converted for perennial energy crops. This figure has been identified elsewhere as the maximum UK land availability for biomass [11]. Therefore, the 2,409,541 ha identified here for England as viable for cultivation of *Miscanthus* within 40 km of the identified potential end uses of feedstock, may require further consideration of competition with other land uses, which could significantly reduce bioenergy generation potential.

4.6. *Other factors affecting total potential*

The complexity of agricultural systems dictates that yield predictions based on model output should be regarded only as a guide [44,45,58]. Inter-annual yield variability with temperature, radiation and precipitation is likely, and yield variation between genotypes interacts with spatial and climate factors [44,60]. Model yield predictions were supplied as three ranges, and although average estimates were used in calculations, this is not a guarantee of feedstock availability. Based on these ranges, total potential cultivation on land identified by this study would range from 29 oven-dry Mt to 35 oven-dry Mt. Annual variation in yield may exceed model predicted ranges, and will be affected by site-specific factors. Also, annually varying spatial patterns of availability of feedstock will interact with transport distance to affect the true cost of supplying a plant. Feedstock type is also significant; yields are identified for a specific *Miscanthus* variant, chosen due to its high yield in field trials in England [44], whilst a mosaic of different species accounting for site factors may give higher total yield [60]. Contracts between plants and farmers tend to be agreed based on minimum expected yield for a specific site, to ensure that the plant has reliable supply [61]. An increase in allowable transport distance may be helpful in enabling demand to be met in years when more local sites experience low yield. Hence, capping transport distances to minimise emissions may diminish feasibility.

In this study, feedstock demand calculations were based on average efficiency values for existing power plants. As well as existing variation in efficiency, future technological improvements in efficiency may affect demand. Coal is a mature technology and CHP already has high efficiency in terms of total output, making efficiency improvements unlikely, although CHP flexibility could increase if future developments improve efficiency at higher proportional electricity generation [2].

A radius of 40 km was used in the analysis presented here to approximate 40 km road transport regions, since it is impractical to incorporate site specific data on potential transport routes. Hence, this approach may generate optimistic estimations of local cultivation potential, particularly in regions with limited road networks. Lower emissions for boat transport may mean that GHG emissions savings can be maintained over longer distances for non-road transport, however costs may be prohibitive.

Pelletisation and torrefaction processing of feedstock to increase energy density are being tested for *Miscanthus* [15]. These processes reduce storage and processing space and costs, and improve fit with the coal plant systems of fuel injection and combustion [61]. Processing would add the complicating factor of the processing plant location to the spatial analysis, but the increased sourcing radius could increase generation scale once there is sufficient confidence in the technology.

Land availability for biomass is based on a holistic GIS assessment of ecosystem services impacts [44], although in practise an in-depth site-specific assessment may identify reasons why land use change for *Miscanthus* cultivation should not or would not take place; for example, due to habitat mosaic impacts on food webs [62], excessive GHG emissions from disruption of soil [63–65] or water resources impacts compared to existing land cover [59,66]. Constraints mapping to produce this data rules out environmentally sensitive landscapes and grasslands; these may be converted for biomass if economically viable, although government grants may not be applicable on environmental grounds. Hence, constraints applied to site selection may over or under estimate potential biomass availability once site-specific assessment of economic and environmental factors has taken place [44].

4.7. *Obstacles to implementation*

The change to a farming system to incorporate uptake of perennial energy crops makes farmer choice an important and perhaps less predictable variable when considering where energy crops may be grown [68]. Change to *Miscanthus* requires high initial investment (in England this is partially offset financially by the ECS financial support [65]) and long-term commitment of land [9,67,68] which may be discouraged by market uncertainty. Supply chain establishment is complicated by the conflict between a need for long-term contracts (both for farmers to commit land [9], and for construction of new plants) and the economic and technical uncertainties surrounding new technology, preventing set long-term pricing. Since imported or alternative feedstocks may be preferred, potential demands identified by this study may not represent a secure market for local feedstock suppliers, making cultivation economically risky. Planned biomass

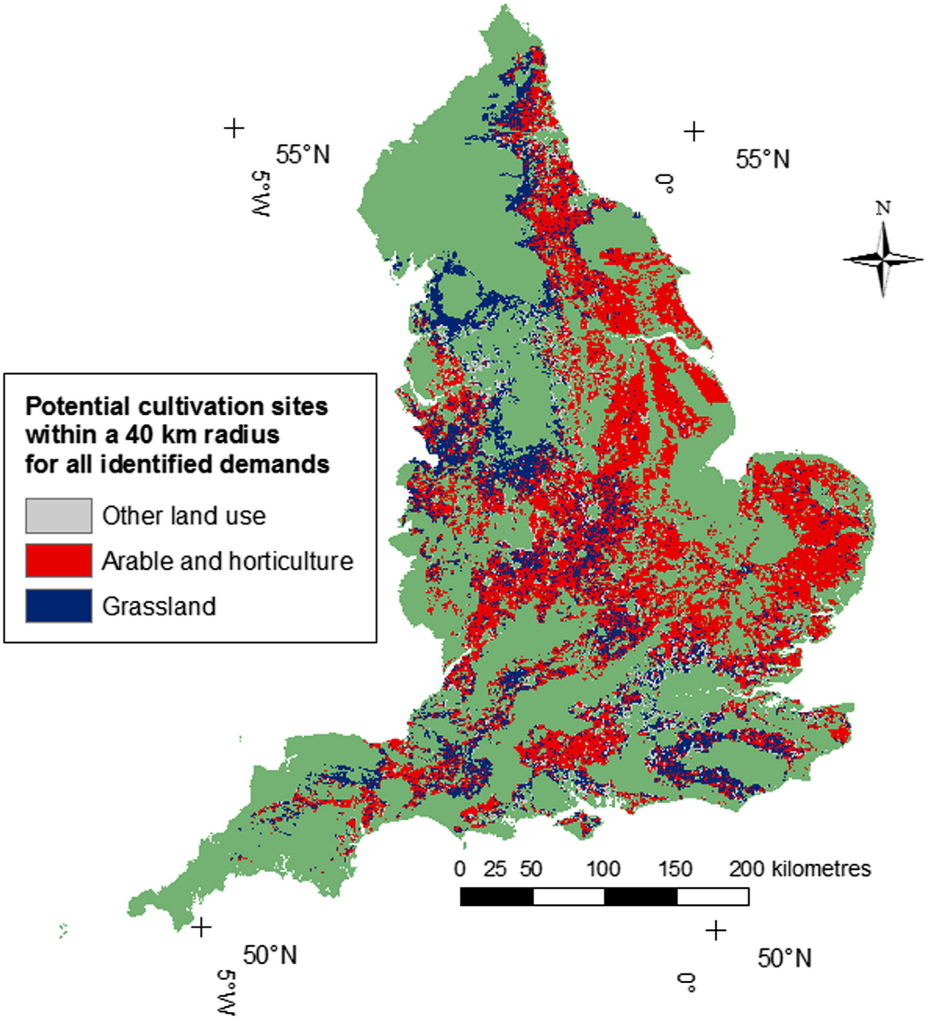
55°N
5°W
0°
55°N
N
Potential cultivation sites within a 40 km radius for all identified demands
Other land use
Arable and horticulture
Grassland
0 25 50 100 150 200 kilometres
50°N
5°W
0°
50°N

Fig. 6 – Map to show potential supply locations within 40 km of identified demand, displayed according to existing land use. This map indicates the extent of arable (red) and grassland (blue) which could be taken up by biomass cultivation. The sites shown have been identified as suitable by constraints mapping, are predicted oven-dry feedstock yields over 9 t ha^{-1} a^{-1}, and are within 40 km of at least one of the three identified end uses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

plants are mostly on the coast, suggesting that plant operators prefer to maintain choice of feedstock suppliers. Investing up the supply chain by plant operators has been suggested as a potential solution to the issue of market and supply chain security [69].

There is a perception of a conflict between cultivation of food or fuel, since it is assumed that food could have been cultivated on land which may be taken up for cultivation of energy crops, and there is evidence of rising food prices and declining food production [70,71]. However the significance of pressure on land varies between countries. Mapping potential cultivation with existing land use for 2007 [72] as shown in Fig. 6, indicates that over 41,227 ha of arable and horticultural land, and over 20,182 ha of improved grassland would be replaced. Highly productive agricultural land was excluded from consideration by constraints mapping (as described in Ref. [44]). Based on land use requirements identified by this research, and assuming average yields for converted land, conversion of arable land would result in a loss equivalent to 0.3 Mt of cereal, which could be offset by reducing the 1.2 Mt net UK export for 2011, although indirect land use change and economic trades off must then be considered. Comparatively, to meet the 2011 UK biofuel target of 27 PJ using wheat bioethanol, 3 Mt of cereal would be required [41], threatening food availability.

For conversion of grassland, CO_2 and N_2O emissions from disruption of untilled soils may have negative consequences in terms of GHG balance, and must be taken into account. Changes to soil and resultant GHG balance may vary between sites with interacting factors such as topography, climate, soil type and land use history [73,74]. This site-specific GHG balance change is important for all land use change, and perennial crops such as *Miscanthus* represent a significant farming system change compared to traditional annual arable crops [35].

Climate and history of DH and associated infrastructure determine the effectiveness and likely uptake. DH is considered likely to be profitable at demand densities over 180 MJ m^{-2} a^{-1} [51]. Even where profits can be predicted over the project lifetime, set up costs and a lack of familiarity with DH may be a significant obstacle to new projects, whereas existing DH may be more conveniently converted to biomass [39].

Policy can be a significant factor in encouraging new energy approaches; for example the renewable heat incentive (RHI) in the UK provides an additional incentive for growth in CHP [75]. However, plans to exclude bespoke feedstock from the RHI if there is significant expansion remove long-term guaranteed returns and may discourage cultivation [9,67,75,76]. Since overall efficiency of CHP is greater for lower electricity to heat ratios (provided a suitable heat off-taker is available) policy should not incentivise electricity over heat, as this would encourage plant inefficiency [16,34].

5. Conclusions

This research expands on previous studies [11,17,41] to further demonstrate the utility of a GIS-based approach to analyse spatial factors affecting potential generation from bioenergy, by relating supply to potential fixed location demand on a national scale. Using the example of England, this paper highlights the significance of overlapping feedstock catchment zones, and the impact on total generation potential of end use allocation of this feedstock. The potential bioenergy generation for England is 383 PJ total generation, which decreases to 76 PJ if DH cannot be implemented, highlighting the importance of overcoming socioeconomic barriers to DH [77]. Compared to meeting UK biofuel targets with wheat ethanol [41], potential *Miscanthus* bioenergy generation for England has less impact on food production, for greater energy generation, supporting previous assertions [6,35] that non-food crops may be a better route for bioenergy.

CHP has a conversion efficiency over double that of co-firing. However, it is economic and not environmental issues that are likely to control the rate of expansion in generation from biomass. Co-firing may be initially cheaper since little investment is required, whereas new district heating would require significant investment in infrastructure, which may deter energy generators. The costs and commitment of land required for perennial feedstock cultivation mean that guaranteed income may be a pre-requisite for cultivation. Where policy has economic implications, it can become a deciding factor, making it crucial that low-carbon future objectives are supported without unsustainable detriment to the environment, food production or other ecosystem services. Encouraging cultivation of biomass feedstock for CHP whilst minimising food security detriment, as well as safeguarding the environment, is a highly complex issue. Ideally, policy incentives and sustainability assessment should reflect this, without adding uncertainty to an already imperfect market.

The GIS approach presented in this paper can be used in any location where datasets are sufficient and can be used as the basis for constraining biomass policy and incentives, if sufficient attention is paid to the caveats outlined in this paper. Through analysis for England, this approach has highlighted clear differences in efficiencies relating directly to end use given the existing energy demand and supply context. We argue that such understanding is essential prior to framing policy which will have land use implications.

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